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ADVISORY CIRCULAR

AIRCRAFT ICE PROTECTION

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Initiated by: FS-140

FOREWORD

1. PURPOSE. This advisory circular contains information relating to the substantiation of ice protection systems on aircraft.

2. REFERENCE. Federal Aviation Regulations, Sections 23.1093(b), 23.1583(h), 25.1093(b), 25.1419, 25.1583(e), 27.1093(b), 27.1583(e), 29.1093(b), and 29.1583(e).

3. SCOPE. The procedures described in this advisory circular are presented for guidance purposes only and are not mandatory or regulatory in nature. Other methods may be equally effective and acceptable.

Acting Director
Flight Standards Service

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CHAPTER 1. TYPES OF SYSTEMS

1. GENERAL. There are four types of systems used for anti-icing or de-icing exposed surfaces. These are:

   a. Hot air systems.

   b. Electrical resistance systems.

   c. Liquid systems.

   d. Expandable boot systems.

   A brief discussion of each type follows:

2. HOT AIR SYSTEMS. Hot air systems are used on most of the large jet transports because of the availability of hot air from the engines, and the relative efficiency and reliability of these systems. Hot air is used to anti-ice or de-ice leading edge wing panels and high lift devices, empennage surfaces, engine inlet and air scoops, radomes, and some types of instruments. Systems whose sources of hot air are separate heat exchangers have also been used where engines cannot supply the required air mass flows or temperatures.

3. ELECTRICAL RESISTANCE SYSTEMS. Electrical systems have been used on several large transport aircraft. These systems are generally de-icing rather than anti-icing because of the large power requirements for continuous operation. Various cycles are devised and tested to provide the most effective system at the least expenditure of power. Because these systems usually require large amounts of power and are less reliable than hot air systems, they have not been widely used on large transport aircraft except for small areas such as windshields, propeller boots, pitot tubes, static ports, radio masts, air scoop inlets, radomes, etc., and in some instances on the horizontal stabilizers.

4. LIQUID SYSTEMS. Liquid systems using glycol, alcohol, or mixtures of these and other chemicals have been devised for such applications as wing panels, windshields, engine inlets, and propellers. Several methods have been devised for applying the liquid to the protected surfaces. For large surfaces, porous materials through which the liquid is pressure fed, have been used. Sprays and slinger rings have also been used in such areas as windshields and propellers. Liquids may be used either to de-ice or anti-ice protected surfaces. The quantity of liquid which can be carried may impose a limitation. Because the flow of liquid must be regulated by small orifices and these orifices are subject to clogging, these systems have not found general usage on large jet transport aircraft.

5. EXPANDABLE BOOT SYSTEMS. Expandable boot systems consisting of sectionalized panels have been used extensively on reciprocating-engine-powered aircraft and on many small turbine-powered aircraft. These panels have been used with good results on wing and empennage leading edges, radomes, and other areas. These systems are generally not suitable for use on engine inlets or propellers where ice ingestion or propeller unbalance would be a hazard.

CHAPTER 2. DESIGN FACTORS

SECTION 1. GENERAL

6. GENERAL. Ice protection systems are designed to provide protection when the aircraft is exposed to the conditions leading to icing likely to be encountered in service. Determination of the design conditions involves consideration of the following:

   a. The meteorological conditions of FAR 25, Appendix C.

   b. The operational conditions which would affect the accumulation of ice on protected and unprotected surfaces of the aircraft.

   c. The operational conditions of the engine and propeller (if applicable) which would affect the accumulation of ice and/or the availability of energy to operate the system.

SECTION 2. METEOROLOGICAL DATA

7. GENERAL. The meteorological data in FAR 25 Appendix C are divided into continuous maximum conditions and intermittent maximum conditions. The two divisions are the results of analyses performed by NACA of data collected from many sources over a period of time. Continuous maximum conditions are defined by Figures 1, 2, and 3 of Appendix C of FAR 25. Intermittent maximum conditions are defined by Figures 4, 5, and 6 of Appendix C of FAR 25. The data in Appendix C are not intended to imply that icing conditions of both types are limited to the altitudes described in Appendix C. The data used to develop the curves were the results of a statistical analysis performed by NACA which recognizes the random nature of meteorological data. Meteorological data are defined in terms of liquid water content (LWC), droplet diameter (Dd), and temperature (T), and each of these parameters is involved in the determination of the design points.

8. LIQUID WATER CONTENT. LWC (gm/m^3) is of prime interest to the designer because it influences the maximum quantity of ice that can accumulate. All of the liquid to which a surface is exposed, however, does not collect on the surface. Water collection is a function of flight speed, airfoil geometry, droplet size, and other ambient conditions, in addition to LWC. Data covering conditions within a specific cloud type indicate that there is a definite relationship between LWC, temperature, pressure altitude, and droplet diameter. Statistical analysis of data covering many icing encounters, in contrast with that shown for conditions in a single cloud type, indicates that high LWCs are associated with high temperatures and low droplet diameters and vice versa. This trend is shown in the FAR curves. Figures 3 and 6 of the FAR curves showing the variation

of LWC factor with distance are primarily of interest in predicting the amount of ice which can accumulate on unprotected surfaces during a selected period of exposure. However, for the design of ice protection systems, the unadjusted values of 17.4 nautical miles for stratiform clouds and 2.6 nautical miles for cumuliform clouds are used to obtain the design LWC value.

9. DROPLET DIAMETER. All the water contained in the swept volume of a cloud formation does not impinge on the exposed surfaces. Impingement rate is a function of droplet size as well as quantity. The larger drops due to their increased inertia have the higher impingement rate. Drops occur in many sizes in nature. The distributions most commonly used are shown in the following table.

TABLE I

Total LW in Each Size Group -- %	a/a_o Distributions				
	A	B	C	D	E
5%	1.00	0.56	0.42	0.31	0.23
10%	1.00	0.72	0.61	0.52	0.44
20%	1.00	0.84	0.77	0.71	0.65
30%	1.00	1.00	1.00	1.00	1.00
20%	1.00	1.17	1.26	1.37	1.48
10%	1.00	1.32	1.51	1.74	2.00
5%	1.00	1.49	1.81	2.22	2.71

The size of droplets contained in a distribution is expressed as the ratio of the average diameter "a" in each group to the volume median drop diameter "a_o." Due to the difficulty in measuring the distribution of droplet sizes in an icing cloud, however, it has become common practice to refer to a mean effective drop diameter--MED. The MED divides a distribution so that the volume of water contained in drops of a larger diameter than the MED is equal to the volume of water contained in drops of a smaller diameter. An MED of 20 microns has been successfully used to determine the water catch rate and an MED of 50 microns has been successfully used to determine the impingement limits. However, the complete range of droplet sizes should be considered to establish the most severe conditions.

10. TEMPERATURE. Temperature affects the severity of an icing encounter in many ways. Data indicate that the highest LWC concentrations occur at the higher temperatures as previously indicated. This trend can be seen in the FAR curves. Temperature affects the impingement computations which involve viscosity, density, and the quantity of heat, Q, required to anti-ice or de-ice a surface. In this respect, a system design is usually chosen such that the Q_A available exceeds the Q_R required for a chosen group of meteorological and operational conditions.

11. USE OF METEOROLOGICAL DATA FOR DESIGN.

a. LWC, droplet diameter, and temperature are used to determine the water catch rate, M_T, and extent of ice accumulation on a surface. The collection rate is given by the following equation:

$$M_T = 0.3296\ E_M\ V(LWC)\ tC$$

where:

M_T =	Mass of water intercepted	lb/hr/ft of airfoil span
0.3296 =	Conversion factor (will vary with the units used)	
E_M =	Collection efficiency of airfoil	%
LWC =	Liquid Water Content	gm/m^3
t =	Airfoil thickness	% of chord length
C =	Chord length	ft.
V =	Airplane speed	MPH

The airfoil thickness may sometimes be expressed as h/c where h is the projected height of the airfoil normal to the flight path. The collection efficiency defined as the ratio of the mass of liquid water collected by a surface to the mass of liquid water contained in the swept volume of the surface at a given angle of attack, is a function of flight speed, droplet size, body geometry, ambient temperature and pressure.

b. The collection efficiency of a surface can be determined either by analysis or test. This requires a knowledge of the flow field around the surface. Flow field data determine the streamlines around a surface, and hence, the drag forces acting on a droplet.

The pressure distribution may be determined analytically or experimentally by wind tunnel or flight tests. Once the pressure distribution is known, the flow field can be calculated.

c. In some cases, the impingement characteristics can be estimated by a "matching technique" by which a particular airfoil section is compared to a model of known impingement characteristics. Plots and tables relating the various functional parameters used to determine collection efficiency are available. "Matching techniques" should be used with caution on sections where the airfoil section is subjected to influences which did not exist when impingement characteristics were established on the reference model. Such influences would include but are not limited to engine air flow into an inlet duct, propeller wash on various surfaces, wing downwash effects on aft mounted engine inlets, etc.

d. The ultimate point at which a droplet impinges on a surface is the resultant of inertia as well as drag forces. A 20-micron droplet diameter is usually used to determine water catch rates; however, the entire range of values should be considered. A droplet diameter of 40 microns is often used to determine impingement limits. In some cases, the water catch due to the increased droplet size may be ignored; however, the manufacturers should show that consideration was given to such limits.

SECTION 3. OPERATIONAL FACTORS

12. AIRPLANE OPERATIONAL FACTORS.

a. The determination of the most severe conditions for which an icing system is to be designed involves consideration of the operational characteristics of the airplane. Operational regimes such as climb, cruise, hold, and descent are usually investigated at various altitudes. For airplanes with low-speed, high-lift devices, the operational regime during which these devices are used may be the most severe. In other cases, the cruise condition may be the most severe because of the lift, drag, or control problems associated with the buildup of ice on exposed surfaces. Service experience indicates that holding in icing conditions for as much as 45 minutes is an operational condition that may be encountered.

b. The airplane attitude can contribute to the formation of ice on critical areas. The type and shape of ice formation, and the surface on which the ice forms are, among other things, functions of airspeed and angle of attack.

c. For a given set of meteorological conditions, the rate and extent of ice accumulation is a function of flight speed as well as airfoil or body geometry.

d. Small bodies moving at high speeds encountering large droplets will exhibit a high collection efficiency. The flow field associated with larger bodies results in a smaller collection efficiency.

e. The duration of the exposure of an airplane to severe icing conditions is dependent on the flight speed of the aircraft and the extent of the icing cloud. However, icing tunnel tests show that the accumulations of ice on a surface are not always in a linear relationship with time, especially for accumulations of glaze ice. Ice growth changes the airfoil characteristics and causes a continual change in collection rate above the initial rate; therefore, extrapolating ice accumulations as a linear function of time can be very misleading.

13. HELICOPTER OPERATIONAL FACTORS. Current development of helicopter rotor system de-icing or anti-icing means has not provided systems or hardware deemed acceptable by helicopter manufacturers. Therefore, all helicopters to date have been restricted against operating in icing conditions. This restriction does not insure that icing conditions will not be encountered inadvertently. Therefore, it is necessary that the powerplant be protected against the effects of ice accumulation as specified in the regulations; however, continuing exposure to icing conditions may cause the helicopter to become incapable of sustaining flight. In view of this, there appears to be little constructive purpose in requiring an indefinite protection of the helicopter powerplant installation against ice conditions as long as the protection that is provided assures a level of safety equivalent to that required by the regulations throughout conditions and duration of exposure under which flight can be maintained.

14. ENGINE OPERATIONAL FACTORS.

a. The engine operational factors to be considered in determining the most severe conditions are directly related to aircraft operational procedures because changes in airplane speed and attitude are usually accompanied by changes in engine power requirements. The prime factors to be evaluated are the quantity and temperature of air available from the engine and the airflow through the engine during the most critical operational mode. These factors are especially critical for evaluation of hot air systems where the air source is the engine. The airflow through the engine is critical in terms of the flow field around the inlet lip and the engine inlet. The flow field must be known in order to determine the heat transfer relationships between the heated surfaces, the hot air used to heat the surfaces, and the quantity of water impinging on the surfaces. During some operational modes, the inlet static pressure and temperature are below ambient. In marginal icing conditions, this reduction in temperature may be sufficient to cause ice to form in the inlet.

b. Engine inlets, inlet air screens, and inlet lips are considered to be more critical with respect to accumulations of ice on surfaces exposed to engine airflow due to the possibility of an appreciable quantity of ice being ingested into the engine. Ice ingestion can cause serious damage to compressor or fan blades. Runback water can also refreeze on unprotected surfaces of the inlet and, if excessive, can reduce engine airflow or distort the flow pattern in such a manner as to excite compressor or fan blades to critical frequencies.

c. Various engine operational modes have an effect on the collection of ice on propeller surfaces of propeller-driven aircraft. Propeller surfaces are treated similarly to other surfaces in determining the extent and degree of ice protection required. The greatest quantity of ice normally collects on the spinner and inner radius of the propeller. Aerodynamic heating and centrifugal force tend to eliminate ice from the other surfaces. Propeller areas on which ice may accumulate and be ingested into the engine should be anti-iced, rather than de-iced, to reduce the probability of ice being shed into the engine.

d. In addition to the foregoing, the buildup of ice on unprotected surfaces and the general operational conditions prevalent during an icing encounter place further emphasis on the necessity for maintaining an acceptable level of power output.

15. HOLDING PHASE. Effective ice protection of an entire aircraft during holding procedures may become the most critical consideration for design of the ice protection systems. The continual growth in numbers of aircraft operations imposes further air traffic burdens at terminal areas where holding is often necessary. Consequently, the selection of suitable altitudes to avoid or reduce the severity of icing becomes more difficult with these increasing operations.

SECTION 4. OTHER FACTORS

16. ICE SHEDDING. When ice is shed during or after an ice encounter, it may create a hazard by entering engine inlet ducts or by striking and damaging other parts of the aircraft. The aircraft design should consider these hazards and appropriate steps should be taken to prevent unwanted buildup and release of large pieces of ice that could cause hazardous malfunctioning or substantial damage to the engine or aircraft. Maximum ice shedding usually occurs after an ice encounter

when the aircraft is flown into outside air temperatures above freezing. Ice can be expected to be shed from wing and empennage leading edges, windshields, the fuselage nose, pitot masts, antennae, propellers, rotors, etc. Engine inlet ducts and other parts of the aircraft located in the path of released ice are susceptible to ice damage. Experience indicates that small turbine engines are more sensitive to compressor blade damage and adverse engine operation during ice ingestion than are the larger turbine engines.

17. ICE SHAPES.

a. The critical shapes that can be expected to form on unprotected surfaces can be established by flight tests in natural ice conditions, if the critical temperature LWC and drop size associated with these shapes can be found.

b. Ice shapes vary with the above factors as well as with airfoil sweep, thickness, and angle of attack.

c. Extensive natural icing and icing tunnel experience has been documented and correlation of laboratory ice shapes with ice shapes observed under natural conditions on a specific airfoil is reasonable.

d. The effects of the maximum shapes and all lesser quantities and shapes of ice on the aircraft flight characteristics should be investigated. This investigation should not be limited to analysis, but should include a demonstration of a capability for continued safe flight and subsequent landing. A flight demonstration of an aircraft equipped with artificial ice shapes can be dangerous if approached with insufficient caution.

e. Wind tunnel and/or dry air flight tests with ice shapes should be utilized. If an ice shape that is most critical for both handling characteristics and performance can be determined, then it is only necessary to flight test the most critical shape; otherwise, various shapes should be flight tested to investigate the aircraft's controllability, maneuverability, stability, performance, trim and stall characteristics for all combinations of weight, c.g., flap and landing gear configurations. Where practicable, the most critical ice shapes should be tested in combination with all other expected ice accretions to determine the full impact on aircraft performance.

18. UNPROTECTED SURFACES.

a. Aircraft normally include surfaces on which ice will accumulate and for which no ice protection is provided. The airplane will be able to operate safely under the specified icing conditions only if the effect of ice accumulation on these surfaces has been shown not to introduce a hazard.

b. To establish the airplane's tolerance to the continuous accumulation of ice on unprotected surfaces, flight tests should explore stratiform icing clouds (continuous maximum Fig. 1) for a period of time representative of today's air traffic "holding" conditions. The "holding" configurations of the airplane (flaps, gear, drag devices) and recommended speed range should be explored and defined. It is recommended that the tests include a continuous exposure for at least 45 minutes. If the handling characteristics are found to deteriorate below those specified for stability and control, the airplane certification limitations should state the maximum holding time. A precautionary note should be provided in the airplane flight manual to warn the crew of the possibility that, during prolonged encounters, ice buildup on the unprotected surfaces may not be visible to the crew.

c. NOTE: There is usually some unprotected protuberance or surface visible to the crew, such as windshield wipers, pod pylons, landing lights, which could serve (by location and ice dimension) as an ice datum. If there is no protuberance normally visible to the crew, it would be helpful to provide one for this purpose.

CHAPTER 3. DESIGN ANALYSIS

19. GENERAL.

a. The overall objective of the design analysis should be that no combination of meteorological conditions in the FAR 25 envelopes coupled with any engine-airplane operational condition in the airplane operational envelope will result in an accumulation of ice on any surface which will cause an unsafe operating condition.

b. Different design approaches are needed for both airframe and powerplant (engine or engine and propeller) ice protection systems. Aircraft surfaces may be more tolerant to ice accretion than engine and engine inlet surfaces, and the design approach applied to an airframe system may differ somewhat from those applied to an engine system. The airplane operational envelope can be precisely defined but the engine and propeller operational envelopes should consider all possible applications and installations. An aircraft surface's greater tolerance to ice accretions should be demonstrated before omitting all possible applications and installations from the performance envelope. Airframe systems may be designed for either complete evaporation or running wet operation in continuous maximum conditions, provided an exposure to such conditions followed by an exposure to an embedded intermittent condition will not cause an unsafe condition to develop. Engine inlets and associated airframe ducting should meet the same general meteorological design criteria.

c. Design margins for each system will be established by the simultaneous consideration of meteorological factors, airplane-engine operational factors, and any other pertinent factor which might be involved.

d. The most critical conditions applicable to the design of engine inlet and propeller systems should be developed from a consideration of the entire array of meteorological and operational conditions within the operational envelope of the engine. Design points should be sufficiently defined in terms of meteorological and operational factors for the agency to determine how the severity of these factors was established. The determination of the most critical conditions should be made with a specific design objective in mind. An evaporative system may be permitted to run wet under some conditions, and some ice buildup may be acceptable if safety of flight is not jeopardized.

e. The frequency and duration of icing encounters also determine the severity of the conditions for which a system should be designed. Continuous maximum conditions interspersed with intermittent maximum conditions occur in the U.S. and other areas of the world, and international usage of airplanes dictates the need for a design to cover this situation.

f. For design purposes, different areas of the aircraft may require a different approach on the basis of the tolerance to ice accumulation without resulting hazard.

20. <u>AIRFRAME SURFACES, WINGS, EMPENNAGE, CONTROL SURFACES, ETC.</u>

a. A choice should be made in the early design stages of the icing system to determine which portion of these areas should be protected. Those surfaces of the airplane directly exposed to stagnation flow conditions usually accumulate the largest quantity of ice. These include the radome, wing and tail surface leading edges, radio masts, air scoops, etc. Leading edge high-lift devices should receive special attention because of their location and functional importance. The selection of the surfaces to be protected is made after a careful consideration of the most severe meteorological and operating conditions, the probable extent of ice accumulations on exposed surfaces, the effects of such accumulations on lift, drag, and controllability of the aircraft, and the operation of aircraft systems. Consideration of climb, cruise, hold, descent, and approach performance should be provided under operating conditions specified. Some ice buildup may be tolerable on some surfaces if the airplane has sufficient power or thrust to offset the additional lift and drag forces and no unsatisfactory operating condition results. Control surfaces may be more critical than airframe surfaces in this respect. The extent of the icing protection needed for various air scoops is directly related to the need for such protection to maintain satisfactory operation of an essential system.

b. After the extent of protection has been determined, a heat balance between the heat "Q_R" required and the heat "Q_A" available should be reached. "Q_R" required is determined by the type of system chosen (evaporative or running wet), the quantity of water impinging on the surface, temperature of the water and air mixture, and the external flow field around the surfaces. Q_A available is determined from an analysis of the engine bleed flow and temperature conditions, at the most critical operating condition. For electrical systems, the power required for the heat input must be determined.

c. The choice between a de-icing and an anti-icing system may be influenced by an assessment of such factors as effect of shedding ice onto other surfaces or engine inlets, the complexity of a cyclic system, and the availability of a sufficient quantity of heat. The power requirements for electrical ice protection systems may influence the choice between cyclic and non-cyclic systems, areas covered by each, and the interval of the cycle. After due consideration of the foregoing design factors, the manufacturer can establish the airframe system design points in terms of LWC, droplet diameter, and temperature together with those factors necessary for the agency to determine by tests that all design objectives have been met.

d. The following charts illustrate, but should not limit, the meteorological conditions considered in the design analysis.

CONTINUOUS MAXIMUM

Temp - ^{o}F.	LWC	Dd
32	0.8	
14	0.6	
-4	0.3	15
-22	0.2	
32	0.5	
14	0.3	
-4	0.2	25
-22	0.1	
32	0.15	
14	0.10	
-4	0.06	40
-22	0.04	

INTERMITTENT MAXIMUM

Temp - ^{o}F.	LWC	Dd
32	2.925	
14	2.5	
-4	1.925	15
-22	1.1	
-40	.25	
32	1.75	
14	1.45	
-4	1.125	25
-22	0.7	
-40	0.15	
32	0.75	
14	0.50	
-4	0.35	40
-22	0.25	
-40	0.05	
32	0.40	
14	0.30	
-4	0.20	50
-22	0.10	
-40	0.05	

The pressure altitude associated with each temperature should be selected from Figures 2 and 5.

e. In addition to the meteorological conditions under consideration, appropriate operational parameters including such factors as speed, altitude, engine power setting, etc., should be varied over the aircraft operating envelope to determine the combination or combinations of meteorological and operating parameters which result in the most critical design point or points. Because of the large number of variables involved in these design considerations, more than one critical design point may exist for both intermittent maximum and continuous maximum meteorological conditions.

f. The design analysis should indicate that no hazardous quantity of ice will form on the surfaces under consideration when exposed to intermittent maximum and continuous maximum icing conditions consistent with the operational needs of the aircraft.

21. ENGINE INLETS, WINDSHIELDS, AND INSTRUMENTS.

a. The accumulation of ice on the engine inlet nose cowl, bulletnose, and other areas of the aircraft which could affect engine operation is generally more critical from the standpoint of continued safe operation than ice accumulation on aircraft surfaces discussed in item 20 above. Design meteorological conditions remain the same, but operational conditions, particularly with respect to the surface flow conditions, may vary considerably. Although a fixed-engine operational condition is assumed for design of the airframe icing system, engine airflow may vary considerably during a relatively stable airplane operational condition. This is due in part to the variation in airplane response to changes in engine thrust or power output. This lag or variation is a factor in the determination of the most critical conditions for these areas of the airplane. Long curved inlets are particularly susceptible to snow, slush, and ice crystal impingement on the curved surfaces. Vortex generators or other boundary layer control devices should be evaluated to determine the effects of ice accumulations on these surfaces.

b. The most probable engine operational mode associated with a particular airplane operational mode is normally the basis for the design of airframe icing systems. However, due consideration should be given to the need for increased reliance on engine thrust or power output during severe icing conditions and to the possibility that the engine may be actually operated through a wide range of power settings during such an encounter.

c. Ice protection should be provided for all instruments essential for safe operation of the airplane which are subject to ice impingement or to runback and refreeze. The functioning of essential static ports should not be adversely affected by ice accumulation, freezing of runback water from forward surfaces, or water and slush from the landing gear during takeoff and landing. It is possible that slush ingestion and water, ingested at a lower altitude, might freeze when the airplane ascends to higher altitudes and lower temperatures. Some of the instruments that might be affected are pitot tubes, EPR total pressure probes, and certain types of stall indicators. These instruments are generally protected by electrical resistance systems because of the small areas involved and the need to maintain ice-free operation in all icing conditions.

d. The forward surfaces of windshields should be protected to provide visibility during the most severe icing conditions. While these surfaces are generally protected by electrical resistance systems because of small areas involved, there is also the need to require duplication to maintain ice-free operation in all icing conditions.

e. The techniques for determining the most critical design points are similar to those previously discussed in item 20.

(1) The design analysis should indicate that the engine inlet ice protection system will preclude the formation of any ice which could adversely affect continued safe engine operation or cause serious loss of power when exposed to the meteorological conditions as defined in Appendix C of FAR 25 in combination with the aircraft operational needs and aircraft envelope.

(2) Engine inlets are frequently designed to be evaporative under continuous maximum icing conditions and running wet under intermittent maximum conditions. Service experience indicates that this approach has been satisfactory provided adequate precautions are taken to prevent hazards due to possible runback and refreeze.

22. ENGINE AND PROPELLER SYSTEMS. In defining the most severe conditions for the design of icing systems for the engine, propeller, and related components, the manufacturer should not only give consideration to the icing envelopes in Figures 1, 2, 4, and 5 of Appendix C to FAR 25, but to the entire environmental and operational envelopes.

a. Engine.

(1) The engine icing system should be designed to cope with the most severe meteorological conditions occurring simultaneously with the most severe engine and/or propeller (if applicable) operational conditions. Critical design

points for both continuous maximum and intermittent maximum conditions should be developed. Procedures for determining water catch rate, impingement data, Q_A available, and Q_R required are similar to those previously discussed for aircraft systems. The flow field around engine surfaces should be based on the pressure and velocity relationships of the air flowing through the engine.

(2) The principal differences in the design approach applicable to airframe and engine systems arise from the need for reliability of the engine during severe icing encounters to insure that an aircraft will have sufficient power to enable it to continue flight to an area of less severe meteorological conditions.

(3) Although the engine manufacturer generally may have some idea of the eventual application of his engine, he cannot be sure that some future application will not be totally different from that planned. Therefore, the ice protection system should not be limited to a specific application or specific airplane operational envelope.

(4) In addition to the foregoing, the buildup of ice on unprotected surfaces of the aircraft and the aircraft operational conditions during an icing encounter place further emphasis on the necessity for reliable engine performance. Engine struts, nose cones, and inlet guide vanes, if unprotected, may be subject to accumulating excessive ice deposits. When heated surfaces are employed for keeping these surfaces free of ice, the possibility of runback and refreezing should be considered. The first-stage fan or compressor blading of axial flow engines should also be evaluated for possible ice accumulation, with the ice protection system operating, when provided, but usually they are minor due to the centrifugal forces present. The larger fan blades may, however, develop accumulations at low r.p.m. near the blade root areas. It is not considered essential to eliminate ice buildup at the engine face, but any ice buildup allowed on an operating engine should be kept to a minimum to prevent possible damage from ice ingestion and to ensure reliable engine operation.

(5) An accumulation of ice on any engine surface would be considered unsafe if it caused a serious loss of power or thrust, caused airflow disturbances which excited harmonic compressor or fan blade frequencies, became large enough to cause serious engine damage when ingested, caused damage to adjacent structure or engine components when detached by centrifugal force from rotating surfaces, caused an unbalance of rotating components which produced vibrations greater

than those for which the engine had been approved, caused damage due to reduced clearance between rotating and stationary components, or caused any other erratic engine operation.

b. Propeller.

Propeller operation would be considered unsafe if an accumulation of ice caused a serious loss of thrust horsepower, caused an unsafe engine condition to develop, caused damage to adjacent structure when detached by centrifugal force, caused vibrations which could result in engine or structural failure, or caused any other erratic engine, propeller, or airplane operation.

23. SUMMARY OF RECOMMENDED DESIGN PROCEDURES. In summarizing the procedures for developing a design analysis, an approach similar to the following may be utilized:

a. Choose a sufficient number of airplane and engine operational conditions to cover that portion of the operational envelope which lies within the meteorological envelopes of Figures 1, 2, 4, and 5 of Appendix C to FAR 25.

b. For aircraft, develop appropriate engine and propeller (if applicable) operational conditions associated with each airplane operational condition.

c. Determine the flow field around the surface under consideration.

d. Select adequate sets of meteorological values in terms of LWC, Dd, and T for both continuous and intermittent conditions sufficient to cover the entire applicable range of values in Figures 1, 2, 4, and 5 of Appendix C to FAR 25, and establish the water impingement rate on the various areas of the surface under consideration.

e. Determine surfaces requiring ice protection.

f. Determine the "Q_R" required to satisfy the system demands.

g. Determine "Q_A" available for the system under consideration.

h. On the basis of the various items above, predict system performance including surface temperatures.

i. Those combinations which result in the most marginal surface temperatures establish the critical design points.

CHAPTER 4. TESTS

SECTION 1. GENERAL

24. GENERAL.

a. The considerations of meteorological and operational factors were discussed in Chapters 2 and 3 to indicate how the performance of an icing system can be predicted from an analysis of a combination of these factors. Chapter 4 outlines procedures for testing ice protection systems in terms of these factors.

b. Assuming that a system has been designed in accordance with the foregoing design approach that the design points can be justified as being the most severe, testing at the design points is all that would be required to show compliance with the regulations. Tests should be adequate to verify the manufacturer's analysis and selection of critical design points.

SECTION 2. TEST METHODS

25. NATURAL ICING FLIGHT TESTS.

a. One of the best methods for determining the performance of any aircraft ice protection system is to subject the aircraft and the protection system to natural icing conditions and to demonstrate that the airplane can be safely operated while exposed to the icing conditions defined by Figure 1 and Figure 4 of Appendix C to FAR 25. Natural icing tests are required prior to certification for operation in icing conditions.

b. For flights in search of icing conditions, it is preferable to select the geographical area and seasonal period and to watch the weather map for the desired wind direction, velocity, cloud condition, and temperature. Efforts should be made to find an area where air traffic will permit step climbs through stratoform clouds to seek out the high LWC level of the cloud.

c. Ice formation resembling those produced in icing tunnels (within the area of the envelope bounded by LWC of 0.3 to 0.55, with drop size of approximately 20 microns, and in a temperature range of 26° F. to 30° F.) has been observed on many occasions within a very narrow altitude range (200 to 500 feet). This sometimes occurs just below a temperature inversion altitude where there is a mild underrunning of cold air (lifting warm air).

d. The flight test aircraft should have instrumentation to determine liquid water content and droplet size or a means of determining ice accretion rate and the extent of impingement from which these parameters can be established. Rotating cylinders, calibrated in an icing tunnel, have been employed but with mixed success because of boundary layer variations and difficulty with storage. A calibrated liquid water content indicator can be used to determine liquid water content. Drop size can be approximated from the extent of impingement on any shape with known impingement characteristics or by other acceptable means. Oil slides have been used with some success with carefully controlled procedures and correlation when feasible with other techniques.

e. State-of-the-art airborne icing measurement instrumentation, however, has shortcomings. A simple but imprecise indicator of the liquid water content and drop size values of Figure 1 in Appendix C is the observation and photographing of ice buildup on an unprotected surface and correlation (corrected for velocity) with similar buildup under measured conditions in an icing tunnel. When the conditions of Figure 1 have been obtained, the airplane should be investigated for handling qualities to explore the effect of ice accretion on the unprotected surfaces.

f. For an airplane of new design (planform) and for aft-mounted engines, where ice shedding from the wing leading edge can cause engine damage or flameout, the aircraft flight test program should require determination of the effects of ice shedding.

g. Finding cumuliform icing conditions of Figure 4 severity involves seasonal, geographical, and time of day considerations. Experience indicates that the most representative and readable condition will occur:

(1) In a mild cold front system with "building" cells.

(2) Over generally flat terrain.

(3) With warmer moist air reaching the freezing level between 8,000 to 12,000 feet.

(4) Flying parallel to the front through a series of altitudes.

This type of frontal system usually provides an escape route to the sunny side for qualitative evaluation and photography of ice shapes and dimensions.

(h) Conditions to be avoided because of hazard or lack of useful data are:

(1) Late afternoon highly active line squalls.

(2) Snow and hail.

(3) Central U.S.A. in "tornado alley."

(4) Contour holes on airborne radar.

(i) The value of natural icing flight tests can vary with the following:

(1) Correlation of test results with analysis predictions.

(2) Ability to compare with previous designs.

(3) Extent of icing tunnel tests as basic criteria.

(4) Extent of successful correlation of flight skin temperature surveys in dry and wet air full-scale tests with similar shapes and temperatures investigated in the icing tunnel.

(5) Correlation of natural icing test buildup on representative or known sections with icing tunnel shapes, considering correction for time and airspeed.

(6) The absence of unprotected ice-catching protuberances, such as antennas, scoops, struts, etc.

26. <u>DRY AIR FLIGHT TESTS</u>. Dry air flight tests can be used to verify many of the design objectives of an icing system. These tests may be conducted as a preliminary to natural icing tests to check the function and performance of all system components and compatibility of systems. Calculated engine bleed air mass flows for developing thrust setting curves can be verified, and models of predicted ice shapes can be installed on unprotected surfaces and evaluated in terms of lift, drag, and controllability factors of the airplane. An analysis of heat requirements and availability at various operational conditions can be performed from data collected during dry air tests.

27. <u>FLYING TANKER TESTS</u>. Flying tanker tests have been used chiefly by the military to verify satisfactory operation of icing systems in simulated icing conditions. Equipping an airplane for this type of test can be very expensive for a manufacturer in terms of the actual time such equipment would be used in a certification program, and the limitations of such equipment in simulating an actual icing encounter.

Turbulence, inability to expose the complete airplane to icing conditions at a given time, and problems in calibrating the LWC and droplet size of the tanker spray are some of the difficulties encountered with tanker tests. Droplet size has not been easily controlled by spray rigs, nor has liquid water content been easily determined. LWC produced by the spray rig is a function of the distance between the test airplane and the rig since the water disperses very quickly. For these reasons, such tests are not generally considered adequate for showing full compliance with the regulations.

28. SELF-CONTAINED SPRAY RIG TESTS.

a. Certain areas or test sections of airplane icing systems can be tested by installing spray rigs on the airplane in such a manner as to cause impingement on the surfaces during flight. Some of the limitations applicable to tanker tests also apply to spray rig tests. Test rigs of this nature are expensive to develop and install on test aircraft.

b. An additional advantage of this type of testing is the ability to control the distance between the spray section and the test section. The downstream meteorological environment produced by an artificial spray cloud is a function, among other things, of the distance between the test section and the spray rig producing the cloud.

c. The major disadvantage of this method is the possible disruption to the flow field around the test surface due to the presence of the rig itself. This feature may produce unrealistic impingement characteristics which are difficult to evaluate. The size and weight restrictions of the spray rig structure also limit the area that can be subjected to the spray. Because of the limitations of this test method, it is not generally considered adequate for showing full compliance with the regulations; however, this does not eliminate its use as a development tool or for testing relatively small areas for icing.

29. ICING TUNNEL TESTS. Icing tunnel tests are perhaps the least expensive and most accurate method for determining the performance of an icing system under various conditions. There are several icing tunnels in existence which have the capability to control LWC, droplet size, and temperature conditions quite accurately over their range of capabilities. The advantages of ice tunnel test facilities are their ability to control the meteorological conditions through a range of values, to simulate a variety of operational conditions, and to measure performance quite accurately. Instrumentation is generally more extensive and accurate than flight test instrumentation. The disadvantages of

ice tunnel tests are their inability to simulate altitude effects or the effects of ice accumulations on unprotected surfaces, and their inability to provide the combined operational and meteorological conditions that exist during an icing encounter of the full-scale airplane. Turbulence, sidewall effects, size, and scaling factors can be problems in ice tunnel tests. Most tunnels are very small and obtaining aerodynamic and thermodynamic similarity for models of large components can be difficult. A dimensional analysis of the aerodynamic and thermodynamic parameters which describe the full-scale system should be undertaken prior to model tests to assure similarity between the full-scale and model-scale systems. Full-scale values may be determined from natural icing flight tests, dry air flight tests, spray rig tests, tanker tests, or any combination of these tests.

30. COMBINATION OF METHODS. Flight tests in natural icing conditions under design point meteorological and operational conditions provide the most desirable method for showing compliance with the regulations. For substantiation, however, a combination of methods may be necessary. The most desirable combination of methods would usually comprise icing tunnel tests at the design points, with dry air and natural icing tests of the full-scale system under actual flying conditions. Data obtained by the flight tests can be used to verify the manufacturer's analysis and ice tunnel data. The flight tests should also assure that no severe operational or design deficiency exists.

31. ICE SHEDDING.

a. The path of ice released from the aircraft is affected by many variables, such as ice shape and density, aircraft attitude and altitude, airspeed, air flow, manner in which the ice is released, etc. Therefore, it may be difficult on some configurations to show that ice released will not enter into engine inlet ducts or strike and damage other parts of the aircraft. A desirable approach for resolving an apparent "ice shedding" problem is to install anti-icing provisions in critical areas. The same procedures used to substantiate other aircraft anti-icing systems are applicable.

b. If anti-icing provisions are not installed in critical ice shedding areas, then investigations should be conducted to show that ice which sheds off of the aircraft will not cause an unsafe condition. "Ice shedding" investigations should be made during and after ice encounters. Sufficient encounters in all intended operation conditions should be made to assure there is no hazard associated with the release of ice. In addition to the usual measurements and observations made during ice encounter tests, the following additional instrumentation and/or observations are suggested:

(1) Motion pictures to record the trajectory of ice released from the aircraft.

(2) Photopanel for turbine-engine-powered aircraft to record EGT, EPR, and RPM for the purpose of detecting adverse effects on engine operation.

(3) Visual examination of the aircraft for damage before and after ice encounters, especially in the area of the engine compressor and inlet.

SECTION 3. TEST PROCEDURES

32. AIRFRAME SURFACES (WINGS, EMPENNAGE, CONTROL SURFACES, ENGINE INLETS, WINDSHIELDS, AND INSTRUMENTS, ETC.) SYSTEMS.

a. Ice Tunnel Tests.

(1) For ice tunnel tests of these areas, design point values of LWC, Dd, and T should be established in the tunnel at the pressure, temperature, velocity, etc., defined by the design operational conditions. Models should be designed to assure that Reynolds numbers and other dimensionless parameters are maintained as closely as possible to the full-scale value. They should be mounted to simulate the flight attitude associated with the most severe conditions. If flaps or other devices are used to produce the proper flow field conditions, instrumentation should be provided to show that test and design values are in general agreement. In an ice tunnel test of an evaporative system, all of the impinging water should evaporate. In an ice tunnel test of a non-evaporative or running wet system, the predicted amount of runback water should not be exceeded and any ice that forms on critical surfaces should be within the limits predicted in the design analysis and confirmed as acceptable by flight tests.

(2) Liquid systems tested in an icing tunnel should preclude ice formation on the protected surfaces for the designed period of protection with flow of temperature depressant fluids within the design value.

b. Tanker or Spray Rig Tests. Tanker tests have been useful as a development tool but can be dangerous or produce misleading results because of sharp variations in the water cloud and catch that come with changes in distance behind the tanker. Spray rig tests of full-scale aircraft may be used in the substantiation of the critical design points, provided the spray can be calibrated to produce the design LWC and droplet diameter and the tests are conducted under flight conditions representative of the design point conditions.

c. Dry Air and Natural Ice Tests.

(1) Dry air and natural icing tests of full-scale aircraft should be conducted as closely as possible to design point conditions to reduce the uncertainty associated with extensive extrapolations. These tests should demonstrate the effectiveness of the icing system under natural conditions. The tests should also provide the means by which the buildup of ice on running wet and unprotected surfaces can be evaluated with respect to the engine operational characteristics and with respect to the lift, drag, and controllability of the airplane. Ridges on models simulating predicted ice accumulations should be installed on full-scale aircraft during dry air flight tests to show that these accumulations will not cause an unsafe aerodynamic condition.

(2) The natural icing tests should demonstrate that no hazardous accumulations of ice occur which could cause an unsafe condition to develop when icing is encountered. Sufficient testing in natural ice conditions should be accomplished to confirm assumptions made in the manufacturer's analysis and to establish that the extrapolations are accurate within acceptable limits.

33. ENGINES.

a. General.

(1) For complying with FAR 33.67, the icing conditions defined by charts in Appendix C of Part 25 are given as the general flight icing conditions which may be encountered. The Appendix C charts cover such a wide range of conditions and combinations of the various icing parameters that numerous data test points would seem to be indicated. However, experience with turbine engines has indicated that the critical conditions can be covered adequately by engine icing tests covering only a few specific conditions coupled with acceptable analyses, dry air tests, rig tests, or experience with similar engines.

(2) The U.S. military services, for many years, have been qualifying engines to two specific conditions for sea level testing. Compliance with the military testing has been

accepted for FAA engine certification in several instances and has provided acceptable results. Recent experience has indicated the desirability of considering the effects of a ground icing fog, which may cause an unsafe condition due to excessive ice accumulation in prolonged ground operation at low-power settings. The following guidelines are provided to assist in establishing acceptable testing programs and to promote uniform levels of compliance.

(3) Engines requiring ice protection systems should have the capability of de-icing the protected surfaces, as it is generally assumed that icing conditions may be encountered in operation without immediate recognition of the fact by the pilot. In the event a satisfactory automatic anti-icing system actuation control is provided, this matter may be recognized; however, current engine protection systems employ manual actuation, necessitating the de-icing capability. A one-minute actuation delay is assumed to cover the probable delay in system actuation.

(4) Engines whose features inherently preclude adverse ice collection and buildup at all times do not require de-icing or anti-icing systems.

b. Acceptable means of compliance.

(1) The engine should be capable of operating acceptably under the meteorological conditions of Appendix C of FAR 25 over the engine operating envelope and under conditions of ground fog.

(2) Experience has indicated that testing to the points set forth in the following table and schedule has been considered a successful means of showing compliance if used in conjunction with the critical conditions determined in the design analysis.

Icing Condition	1	2	3
Liquid Water Content, gr/meter^3	2.	1.	2.
Atmospheric temperature, $^{\circ}$F.	23.	-4.	29.
Mean effective water droplet diameter, microns	25.	15.	40. minimum

(a) Operate the engine steadily under icing conditions 1 and 2 for at least 10 minutes each at takeoff setting, 75 percent and 50 percent of M.C. and at flight idle setting, then accelerate from flight idle to takeoff. If ice is still building up at the end of 10 minutes, continue running until the ice begins to shed or until the engine will no longer operate satisfactorily.

(b) Operate steadily at ground idle setting for at least 30 minutes under icing condition 3 followed by acceleration to takeoff setting.

(c) While at cruise and flight idle, for engines with icing protection systems, operate for at least one minute in the icing atmosphere prior to turning on the icing protection system.

(3) Engine operation in these icing conditions should be reliable, uninterrupted, without any significant adverse effects, and include the ability to continue in operation and accelerate. Some power reduction is acceptable at idle power settings but all other operation should be unaffected.

(4) Special consideration and tests should be conducted to adequately substantiate:

(a) Engines with inlet screens.

(b) Engines with air passages which might accumulate snow or ice due to restrictions or contours.

(c) Unprotected surfaces upon which ice may build up in rare instances to significant degrees for longer exposures than specified above.

34. <u>HELICOPTER ENGINE INLET AND ROTOR</u>. If comparative testing of the engine inlet and the rotor system is to be used to establish equivalent safety, it should be conducted under conditions which provide known values for water content, droplet size, and temperature. However, cloud horizontal extent need not be considered if it can be positively established that all icing conditions which result in significant ice accretion on the engine inlet also result in intolerable ice accumulations on the helicopter rotors. Sufficient variations of the icing parameters should be investigated to assure that the condition found critical for the engine inlet is also critical for the rotor system. Experience has shown that at high ambient temperatures (above 25° F.), rotor ice shedding occurs at time intervals which prevent ice buildups.

SECTION 4. FINDING ICING CONDITIONS FOR TEST PURPOSES

35. GENERAL.

a. Aircraft icing has been the subject of a great deal of discussion, but actual operational encounters with icing conditions have been rarely documented. Scheduled flight operation in icing conditions is not unusual, while finding natural icing conditions for testing aircraft ice protection systems can be a problem during aircraft certification programs. For example, after a fruitless search for icing conditions in the Northwest during the month of February, the test aircraft accumulated a heavy buildup of ice on a letdown to home base.

b. In another related experience, it was reported that on a flight between Shannon and London in a stratoform cloud at 6,000 feet (temperature 28° F. to 30° F.), a very heavy accumulation of ice was observed on the unprotected surfaces. The captain (with 20,000+ hours flying time) stated that it was the heaviest ice accumulation he had ever seen. Another altitude was requested but it was denied because 3,000 ft., 4,000 ft., and 7,000 ft. altitudes were occupied. Airplanes at other altitudes reported only a trace of ice.

c. These experiences and others support the contention that ice intensity corresponding to Figure 1, Appendix C, is confined to a small vertical segment of the atmosphere and that one could look a long time at other altitudes and honestly report that "we could not find ice."

d. In another cited instance, two Convair 240's aircraft, one northbound and one southbound, were using the same airway over Philadelphia at 1,000 feet vertical separation. The northbound airplane encountered severe ice, while the southbound encountered just a trace of ice.

e. The operational pilot and the test pilot have no way of predicting or seeing the level at which high accretion rate would be encountered. One would like to avoid it and the other wants to find it. The solution for both is the same. If possible, change altitude.

f. The test group should make arrangements to "work" an area where an altitude band can be cross-sectioned; otherwise, time could be needlessly wasted.

g. The rate of accretion, ice shape, and ice hardness varies over the envelopes of Figures 1 and 4 of FAR 25, Appendix C. Figures 1, 2, 4, and 5 are a compilation of service experience and icing tunnel data which define the likely areas in nature where ice would be encountered.

h. Ice accretion will occur on any object moving through a cloud when the temperature is below freezing.

(1) The rate of ice buildup will vary with:

(a) The water density of the cloud, i.e., liquid water content.

(b) The velocity of the object.

(c) The size and shape of the object.

(d) The temperature of the air and the temperature of the object.

(e) The temperature of the water drops.

(2) The shape and consistency of ice buildup will vary with:

(a) Temperature of the object, the cloud, and the water drop.

(b) The velocity of the object, as it (the temperature rise) affects the surface temperature.

(c) Thickness ratio of the object and "sweep" with respect to the free stream.

These items have been listed to emphasize the fact that ice accretion on unprotected portions of the airplane, or on wing and tail surfaces with anti-icing/de-icing system turned off, varies with the factors previously mentioned. Ice buildup observed by the flight crew on various parts of the airplane may be compared with NACA ice tunnel data accumulated under controlled conditions of liquid water content and droplet size. The flight crew can also estimate the icing intensity of the stratus cloud they are exploring and determine whether they are actually traversing FAR 25, Appendix C, conditions. If they are not collecting ice at the desired rate, they should move to another altitude in search of the high water content level.

36. <u>FINDING ICE IN STRATOFORM CLOUDS</u>. The following conclusions are based on practical experience and success in finding icing conditions in stratoform cloud conditions:

a. The water catch rate or ice accretion rate will decrease with decreasing temperature below $+32^{\circ}$ F.

b. Dense stratoform clouds being lifted to higher altitude over rising terrain occasionally have LWC higher than required. Flight over mountainous terrain should be avoided because of inconsistencies in the relationship between liquid water content and temperature.

c. For given temperature, the shape of the ice accretion will vary with droplet size.

d. Conditions approaching rain, such as large drops spattering on the windshields or intermittent sharp increase in catch rate, should be avoided. These conditions indicate that there is a rain-producing cloud above the stratoform cloud and that intermittent (Figure 4) conditions are being encountered.

e. It should be recognized that the variation in LWC with temperature (for a given drop size) in Figure 1 is an expression of the predicted variation of cloud density with temperature. One should choose what is believed to be critical temperature for the type of protection system involved.

f. Icing conditions of the intensity of Figure 1 frequently occur in very moist air masses blowing inland from warmer seas, such as the Gulf of Mexico, the Japan current, and the Gulf Stream.

g. The super-saturated clouds lift and cool as they move over the land mass. Random seeking of ice is time consuming and wasteful. Adequate planning will increase the chance of success. It is advisable to wait until the weather map shows the correct direction of air movement, heavy clouds over a large area, and freezing level at 6,000 to 8,000 feet; then crisscross the area in step climbs.

37. FINDING ICE IN CUMULIFORM CLOUDS.

a. The meteorological condition which yields reasonably consistent icing can be found in a mild or building (cold) frontal system.

b. The weather map, the patience to await the formation of icing conditions, the ability to start the flight on short notice, and airborne weather radar are the best tools to locate this condition.

c. Intense line squalls should be avoided, such as those prevalent in "tornado alley" in central U.S. and all "contour holes" in radar. These conditions contain extreme vertical air currents, which produce large variations in LWC, drop size, and temperature. The ice catch in severe line squalls will probably be very erratic and conditions change so rapidly that instrumentation is useless.

d. Also, it is best to avoid mountainous areas, because the mechanical lifting causes erratic vertical variations in temperature and only complicate finding the correct altitude (temperature).

e. Fall and early spring are generally the best seasons to find ice. Excessive snow usually occurs in winter and hail usually occurs in summer. The ideal cold front can provide the opportunity of making runs at a series of altitudes parallel to the front and yet provide an escape route to the sunny side to photograph unprotected portions or ice-measuring rods.

CHAPTER 5. SUMMARY OF RECOMMENDED PROCEDURES FOR TYPE CERTIFICATION

38. AIRFRAME MANUFACTURER. The airframe manufacturer should submit a design analysis which has as its prime objective the determination of the critical design points and the prediction of performance of protective systems for those areas of the airplane for which he has certification responsibility. The selection of these points should involve consideration of all the factors covered in this advisory circular. The manufacturer's test proposal should be submitted and agreement reached on procedures before testing is begun.

39. ENGINE MANUFACTURER. The engine manufacturer should submit a design analysis which has as its prime objective the establishment of sufficient critical design points to assure that the engine can function adequately in continuous maximum and intermittent maximum conditions. The selection of these points should involve consideration of all the factors covered in this advisory circular. The manufacturer's test proposal should be submitted and test procedures agreed upon before testing is begun. Testing should be conducted at sufficient points throughout the power or thrust range to demonstrate that no unsatisfactory engine operational feature exists under these conditions.

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